Charm muoproduction by cosmic rays

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Abstract

Narrow muon bundles in underground detectors permit to study muoproduction reactions that take place in the surrounding rock. We analyze the relevance of a QED+QCD reaction, muoproduction of "open charm". The contribution to double muon events is estimated to be 4% of the one due to QED "trident" process, for an ideal detector located under a rock depth of 3 km water equivalent, and an observation threshold of 1 GeV.

In recent year, there has been a certain experimental [1, 2] and theoretical interest [3, 4, 5, 6] around the topic of "narrow muon bundles" (multiple muons with a lateral separation less than a few meters) in underground detectors. These events have been observed as a peak at small lateral separation, and interpreted as a flux induced by the energetic muons produced in the atmosphere, which propagate underground. Thence, an analysis of these events requires to consider high energy muoproduction processes, in the rock surrounding the detector.

Up to now, the process considered was the muon "trident" reaction [7] $\mu^\pm Z \to \mu^\pm \mu^+ \mu^- Z$, where a muon pair is formed in the field of the nucleus[1]. For muons propagating in high Z materials an amplification factor Z^2/A (= 5.5 for standard rock, A=22 and Z=11) is present, due to coherent character of the reaction. This interpretation has been pursued since the first evidences obtained in cosmic ray experiments [9]. The trident reaction leads mostly to narrow bundles of three or two muons in an underground detector (one produced muon may stop before reaching the detector); a reference ratio in an ideal detector is of 3 double muons *per* triple muon, for a threshold of observation $E_h = 1$ GeV, and a depth $h = 3$ km w.e. of standard rock. Recent studies [5, 6], however, suggest that existing interpretations are insufficient to quantitatively account for the whole "narrow muon" data set.

[1] It is assumed that an effective rejection of photoproduced pions and photons can be achieved.

In this work we analyze the role of another high energy process as source of "prompt" muons: muoproduction of charmed states due to cosmic rays, whose relevant energies range from $E \sim 20$ GeV up to several TeV's[2] (for studies in laboratory, see [10]). More specifically, we are concerned with the "open charm" reaction of muoproduction: $\mu^{\pm}N \to \mu^{\pm}c\bar{c}X$ (X denotes a byproduct which does not concern us). This process is stipulated by QED and QCD interactions, while weak interactions provide the instability of charmed states: $c \to X_c \to \mu X$.

In order to obtain a simple estimate of the flux of double muons due to this process, we adopted the collinear approximation, considering only how the initial muon energy E branches into those of the final muons, and proceeded in the following way:

1) First, we calculated the cross section of muoproduction $d\sigma_{\mu N\to\mu c\bar{c}X}/dE'dE_c$ at leading order in α_s, double differential in the energies of the scattered muon, E' and of the charm, E_c. This can be done with a limited effort by following the calculations documented in [11], where the cross section integrated over the hadronic phase space $d\Phi_{hadr}$ was obtained: In fact, neglecting the gluon mass, we have $d\Phi_{hadr} = dE_c/(8\pi E_\gamma)$, where $E_\gamma = E - E'$ is the energy of the virtual photon emitted by the muon[3]. We multiplied the cross section by a factor $K_{QCD} = 2$, to roughly account for NLO QCD effects [12] (in the actual calculations, that require integrating over the photon virtuality Q^2 and the gluon momentum fraction x, we use the GRV98 gluon distribution [13], and set: $m_c = 1.35$ GeV, $\alpha_s(2m_c) = 0.26$). The differential cross section increases with E' (the "$1/v$ behavior"), markedly but not dramatically for the energies of interest; instead, it is rather mildly distributed in E_c. The total cross section is large, 5×10^{-32} cm^2 for $E = 1$ TeV (slightly greater than the trident cross section at these energies), and increases with E, mostly due to the smaller values of x that are probed by the virtual photon ($x_{min} = 2m_c^2/(ME_\gamma)$).

2) We estimate the probability that a charm yields a muon with a certain energy fraction, $dP_{c\to\mu}/dz$, where $z = E''/E_c$, by first hadronizing the charm into a D meson, using the normalized distribution of [14] with $\epsilon_D = 0.135$, and letting it decay with a $K_{\mu 3}$ distribution (that is, retaining only the D mass, and neglecting the Q^2 dependence of the form factors). The resulting normalized probability falls strongly with the energy fraction z; the average value is $\langle E''\rangle = 0.15 \times E_c$. We took as an effective branching ratio of charm into muons the

[2]We neglect the energy loss in the rock of the hadrons, for a 200 GeV $D^{\pm}$ meson travels on average just 3 cm in the rock before decaying.

[3]Also, it is useful to relate E_c to the zenith angle and velocity of emission in the gluon-gamma c.m.s. as follows: $E_c/E_\gamma = (1 + \beta_c^* \cos\theta_c^*)/2$, where $\beta_c^* = \sqrt{1 - 4m_c^2/(p+q)^2}$ (p and q are the momenta of the gluon and of the virtual photon)

value $BR_{c\to\mu} = 8\%$ [15], and multiplied the result by two, to account for the fact that a charm or an anticharm can yield a muon[4]. Notice, incidentally, that the corresponding yield of triple muon is negligible, due to an *a priori* 4% suppression factor.

3) At this stage, we can calculate the cross section $d\sigma_{\mu N\to\mu\mu}/dE'dE''$, where E'' is the energy of the produced muon, and, with that, the cross section $\sigma_{\mu N\to\mu\mu}(E,f)$ for production of two muons with a fractions greater than f of the initial muon energy [5] E. Due to the behaviors of $d\sigma_{\mu N\to\mu c\bar{c}X}$ and $dP_{c\to\mu}$ with E' and E'' mentioned above, this cross section diminishes dramatically with f; when $E = 150$ GeV, it drops down by one order of magnitude already when $f \approx 0.1$ (at $E = 1.2$ TeV, the same happens at $f \approx 0.07$). This cross section enters the elementary yield of double muons underground, which depends linearly on the infinitesimal depth crossed dh' (in gr/cm^2):

$$dY_{\mu\to\mu\mu}(E, E_{h'}) = dh' \times N_A \times \sigma_{\mu N\to\mu\mu}(E,f) \quad \text{where } f = \frac{E_{h'}}{E} \tag{1}$$

N_A is the number of nucleons[6] in 1 mole (which, when multiplied by dh', gives density of targets *per* cm^2). The energy losses are evaluated in continuous energy loss approximation, $E_{h'} = (E_h + \epsilon)\exp[\,(h - h')\,/\,h_0\,] - \epsilon$, where $\epsilon \approx 600$ GeV and $h_0 \approx 2.5$ km w.e. are phenomenological parameters, and $E_h = 1$ GeV is the threshold for detection. Multiplying the yield by the approximate expression of the single muon flux, given in [16], we obtain the double muon flux induced by "open charm" reaction at a given depth h:

$$F_{\mu\mu}(h) = \int_0^h \int_{2E_{h'}}^\infty \frac{dF_\mu}{dE}\, dE\, dY_{\mu\to\mu\mu}(E, E_{h'}) \tag{2}$$

(notice that E is the energy at the depth where the reaction takes place, which we relate to the energy at the surface E_0, once again in continuous energy loss approximation). The results are shown in the figure, for muons arriving from the vertical direction.

The contribution of open charm reaction is not large; for instance, at a depth of 3 km w.e. it is just 4% of the one due to the trident process. Equivalently, it can be compared with the flux of single muon: $F_{\mu\mu}/F_\mu = 7 \times 10^{-6}$ (open charm) and 1.8×10^{-4} (trident). For an ideal detector, it would require the accumulation of ~ 600 narrow double muon events, to be statistically interesting. Also, this contribution may be not negligible if very reliable QED predictions were obtained. The smallness of the result has to be attributed to the value of

[4]Existing underground detectors do not distinguish between "same charge" and "opposite charge" double muon events.

[5]We consider only those events whose vertex is *not* contained in the detector. Those events profit of a large effective target mass, and correspond, in a sense, to the celebrated neutrino-induced single muon signal.

[6]We assume that a nucleus counts as A independent nucleons: $\sigma_{\mu A\to\mu\mu}(E,f) = A \times \sigma_{\mu N\to\mu\mu}(E,f)$.

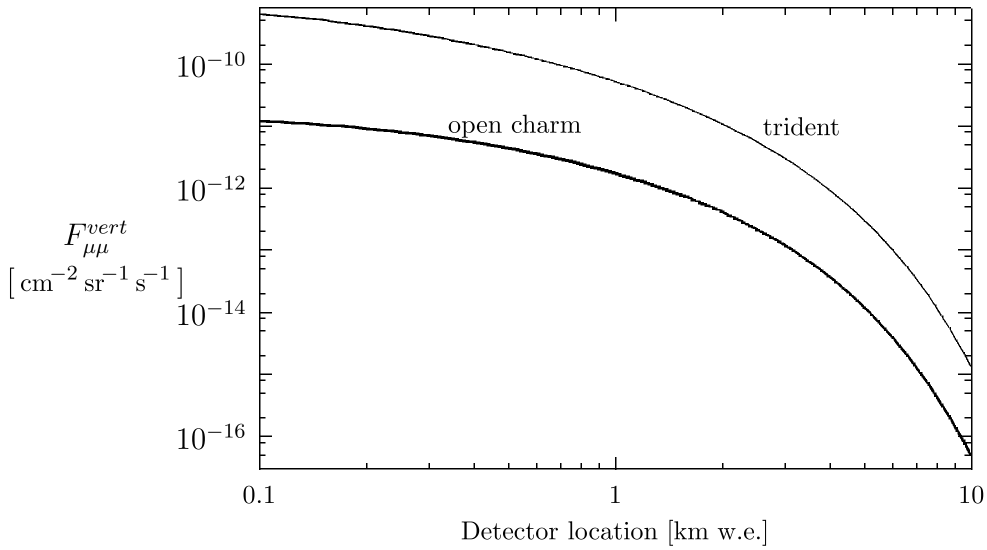

Figure 1: Flux of narrow double muons due to open charm formation (thick curve) and to the trident reaction (thin curve, calculated with the cross section given in [5]).

$BR_{c\to\mu}$, and to the effective leakage of energy of the virtual photon, during the conversion $\gamma^* \to c \to D \to \mu$.

The following remarks illustrate some aspects of this result:

(a) going to shallower depths, the double muon flux increases, though less rapidly than the single muon flux: in fact, the effective target increases with the depth (but, of course, also the background increases);

(b) conversely, in deeper sites the relative contribution of the open charm process becomes more important, due to more energetic primaries–E increases (but there are practical limitations, due to live-time and area of installation);

(c) keeping the depth fixed, and changing the angle of observation, there is an increase of $F_{\mu\mu}$ moving toward the horizon, directely related to the increase of F_μ (but the actual geometry of the rock in the underground site has an essential role in practical considerations);

(d) in water or ice, the trident curve would reduce by ~ 3, due to the $\langle Z^2/A\rangle$ factor, which would make more important the open charm contribution (but it should be reminded that no plan exists to have a large installation underwater or under-ice, able to achieve a good discrimination at small lateral distances).

In conclusion, it seems to us rather difficult to account for a large fraction of narrow muon bundles on the basis of the open charm process[7]. In other words, the possibility to

[7]Even if it should be clear that the quoted figures have a rather large uncertainty, mostly due to the actual value of the charm mass, but also in view of the approximate character of present estimate.

study heavy quark physics with existing underground detectors is quite limited.

For the perspectives, we consider interesting the possibility to achieve energy and charge identification of the muons in future underground detectors. However, even if it will be possible to obtain sufficient statistics and control of the systematics, an attempt to proceed further and extract a signal of production of heavy quarks from studies of narrow muon bundles will need more refined calculations: To describe the NLO effects [17], hadronization, and decay of charmed states [18, 19]; but also those effect in the muon propagation, that are necessary to model the lateral distribution of the events in the underground detectors [20, 21, 6] (possibly, considering the relatively large transverse momenta $p_\perp \sim m_c$ that result from production, hadronization, and decay).

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References

[1] M. Ambrosio *et al.* [MACRO Collaboration], "High statistics measurement of the underground muon pair separation at Gran Sasso," Phys. Rev. **D60**, 032001 (1999) [hep-ex/9901027].

[2] M. Aglietta *et al.* [LVD Collaboration], "Multiple muon events observed in the LVD experiment," Nucl. Phys. B Proc. Suppl. **35** (1994) 243.

[3] V. A. Kudryavtsev and O. G. Ryazhskaya, "Muon pair production by muons and narrow muon bundles underground," Nuovo Cim. **C21**, 171 (1998).

[4] G. Battistoni and E. Scapparone [MACRO Collaboration], "Hints of $\mu + N \to \mu + N + \mu^+\mu^-$ process observation with the MACRO experiment," hep-ex/9902018.

[5] S. R. Kelner, R. P. Kokoulin and A. A. Petrukhin, "Muon pair production by high energy muons and muon bundles underground," *Prepared for 26th International Cosmic Ray Conference (ICRC 99), Salt Lake City, Utah, 17-25 Aug 1999.*

[6] V. A. Kudryavtsev, E. V. Korolkova and N. J. Spooner, "Narrow muon bundles from muon pair production in rock," Phys. Lett. **B471**, 251 (1999) [hep-ph/9911493].

[7] S. J. Brodsky and S C. C. Ting, "Time-like momenta in quantum electrodynamics," Phys.Rev. **145** 1018 (1966); J. D. Bjorken abd M. C. Chen, "High energy trident production with definite helicities," Phys.Rev. **154** 1335 (1967); G. Reading Henry, "Trident production with nuclear targets," Phys.Rev. **154** 1534 (1967); S. R. Kelner, "Pair production in collisions between a fast particle and a nucleus," Sov. J. Nucl. Phys. **5** (1967) 1092 and [5, 8]; M. J. Tannembaum, "Muon tridents," Phys.Rev. **167** 1308 (1968) (the first Montecarlo analysis); J. LeBritton *etal*, "Trimuon and dimuon events produced by 10.5 GeV/c μ^- on lead," Phys.Rev. **D23** 1 (1981).

[8] S. R. Kelner, Yu. D. Kotov and V. M. Logunov, "Underground muon groups," Sov. J. Nucl. Phys. **21** (1975) 394.

[9] M. L. Morris and R. O. Stenerson, "Muon-pair production by cosmic-ray muons," Nuovo Cim. **B53**, 494 (1968).

[10] For seminal works: M .A. Shifman, A. I. Vainshtein and V. I. Zakharov, "Photoproduction of charmed particles and asymptotically free field theory," Phys. Lett. **B65**, 255 (1976); C. Chang, K. Wendell Chen and A. Van Ginneken, "Dimuon and trimuon final states in deep inelastic muon scattering," Phys.Rev. **D39** 519 (1977). See also V. Barger, W. Y. Keung and R. J. Phillips, "Multi - Muon Production By Muons," Phys. Rev. **D20** (1979) 630. Further experimental studies and progresses are due to fixed target experiments, operated below 300 GeV (for a review see *e.g.* S. P. Ratti, "Charm baryon decays in fixed target experiments," *Prepared for Workshop on Heavy Quarks at Fixed Target (HQ 93), Frascati, Italy, 31 May - 2 Jun 1993*) and to the HERA e-p collider, which corresponds to a considerable energy in the lab. frame, $E \approx 45$ TeV (see for instance: L. K. Gladilin [H1 and ZEUS Collaborations], "Open charm production at HERA," Nucl. Phys. Proc. Suppl. **75B** (1999) 117.)

[11] J. P. Leveille and T. Weiler, "Characteristics Of Heavy Quark Leptoproduction In QCD," Nucl. Phys. **B147**, 147 (1979).

[12] R. K. Ellis and P. Nason, "QCD radiative corrections to the photoproduction of heavy quarks," Nucl. Phys. **B312**, 551 (1989); J. Smith and W. L. van Neerven, "QCD corrections to heavy flavor photoproduction and electroproduction," Nucl. Phys. **B374**, 36 (1992); E. Laenen, S. Riemersma, J. Smith and W. L. van Neerven, "$\mathcal{O}(\alpha_s)$ corrections

to heavy flavor inclusive distributions in electroproduction," Nucl. Phys. **B392**, 229 (1993).

[13] M. Gluck, E. Reya and A. Vogt, "Dynamical parton distributions revisited," Eur. Phys. J. **C5**, 461 (1998) [hep-ph/9806404].

[14] C. Peterson, D. Schlatter, I. Schmitt and P. Zerwas, "Scaling violations in inclusive e^+e^- annihilation spectra," Phys. Rev. **D27**, 105 (1983).

[15] C. Caso *et al.*, "Review of particle physics," Eur. Phys. J. **C3** (1998) 1.

[16] T. K. Gaisser, "Cosmic rays and particle physics," *Cambridge, UK: Univ. Pr. (1990)*, page 71.

[17] See for instance: B. W. Harris and J. Smith, "Invariant mass distributions for heavy quark - anti-quark pairs in deep inelastic electroproduction," Phys. Lett. **B353**, 535 (1995); E. **B359**, 423 (1995) [hep-ph/9502312]; B. W. Harris and J. Smith, "Heavy quark correlations in deep inelastic electroproduction," Nucl. Phys. **B452**, 109 (1995) [hep-ph/9503484].

[18] For a work oriented toward cosmic ray physics, see E. V. Bugaev, A. Misaki, V. A. Naumov, T. S. Sinegovskaya, S. I. Sinegovsky and N. Takahashi, "Atmospheric muon flux at sea level, underground and underwater," Phys. Rev. **D58**, 054001 (1998) [hep-ph/9803488].

[19] J. D. Richman and P. R. Burchat, "Leptonic and semileptonic decays of charm and bottom hadrons," Rev. Mod. Phys. **67**, 893 (1995) [hep-ph/9508250].

[20] P. Lipari and T. Stanev, "Propagation of multi-TeV muons," Phys. Rev. **D44** (1991) 3543.

[21] P. Antonioli, C. Ghetti, E. V. Korolkova, V. A. Kudryavtsev and G. Sartorelli, "A three-dimensional code for muon propagation through the rock: MUSIC," Astropart. Phys. **7** (1997) 357 [hep-ph/9705408]; see also [6].

[22] V. S. Berezinsky, V. A. Kudryavtsev and O. G. Ryazhskaya, "Photoproduction of charmed particles and generation of muons in electromagnetic showers," Yad. Fiz. **46** (1987) 1716 [Sov. J. Nucl. Phys. **46** (1987) 1026]